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Micrometeorites and Their Implications for Meteors

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Abstract Micrometeorites (MMs) are extraterrestrial dust particles, in the size range 25–400 μm, recovered from the Earth's surface. They have experienced a wide range of heating during atmospheric entry from completely molten spherules to particles heated to temperatures <300°C that have retained low temperature minerals. The majority of MMs have mineralogies, textures and compositions that strongly resemble components from chondritic meteorites suggesting these correspond to sporadic, low geocentric velocity meteors. Changes in MMs due to entry heating, however, have implications for meteoric processes in general that may allow the observed behaviour of meteors to be directly related to the material properties of their meteoroids.

Keywords Micrometeorites · Meteors · Asteroid · Comet

1 Introduction

Micrometeorites (MMs) are that fraction of the extraterrestrial dust flux that survives atmospheric entry to be recovered from the Earth's surface. These particles are mostly in the size range 50–1,000 μm and unlike the larger meteorites (>1 cm), recovered from the Earth's surface, and smaller interplanetary dust particles (<30 μm), collected in the stratosphere, are likely to include the surviving remnants of meteors. Micrometeorites can, therefore, provide valuable constraints on processes operating during atmospheric entry of small meteoroids that are particularly applicable to the interpretation of meteor phenomena.

Micrometeorites have been collected in regions of the Earth's surface where the abundance of terrestrial particles is low: (1) deep sea sediments (Brownlee 1985),

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(2) glacial lakes in Greenland (Maurette et al. 1986), and (3) Antarctic blue ice and snow (Maurette et al. 1991; Taylor et al. 1998). Large numbers of relatively pristine particles have been collected by melting and filtering of Antarctic ice and snow. These Antarctic MMs are mostly >50 μm since terrestrial dust is very abundant at small sizes.

Extraterrestrial dust is also collected in the stratosphere by NASA ER-2 aircraft. These samples are known as interplanetary dust particles (IDPs) and are mostly smaller than 30 μm. These materials include particles that are very different from MMs collected from the Earth's surface (Rietmeijer 1998). The implications of these materials for meteors has been considered by Rietmeijer (2000), the nature of the particles will not, therefore, be described in detail in this paper.

Previous studies of MMs have focused primarily on their nature and identity of their parent bodies, often through mineralogical, chemical and isotopic comparisons with meteorites (Genge et al. 1997; Kurat et al. 1994). The current paper examines the implications of MMs for the atmospheric entry of micrometeoroids and meteor phenomena.

2 Identification and Analysis of Micrometeorites

Definitive evidence for extraterrestrial origin of MMs has been made on the basis of cosmogenic nuclei and noble gas measurements that demonstrate exposure to solar radiation in interplanetary space as dust particles (Olinger 1990; Raisbeck and Yiou 1989). The identification of dust particles as MMs, however, can be made on one or more of a number of other non-isotopic criteria (Genge et al. 2008). Features that strongly suggest an extraterrestrial origin are any of: (1) the presence of a partial or complete shell of magnetite around MMs, which is thought to arising from entry heating (Toppani and Libourel 2003; Toppani et al. 2001), (2) the presence of Ni-bearing iron metal and/or sulphides, and (3) a solar bulk composition for major and minor rock forming elements. Features that are less determinative are: (1) high CaO, Cr_2O_3 olivines and very FeO-poor olivines that are exceedingly rare in terrestrial rocks (Brearley and Jones 1998), (2) vesicular surface melt layers (Genge 2006), and (3) spherical particle morphologies.

Separation of collected MMs is achieved by manual picking under a binocular microscope, principally on the basis of the presence of magnetite rims, indicated by a black colour, and spherical or lobate particle shapes, which may indicate melting. The extraterrestrial nature of particles is confirmed by analytical scanning electron microscope observations on polished samples.

3 Micrometeorite Types

Two main groups can be identified on the basis of surviving pre-atmospheric textures: (1) fine-grained MMs (FgMMs), which are dominated by a fine-grained porous groundmass of micron-sized mineral grains, and (2) coarse-grained MMs (CgMMs), which are dominated by anhydrous silicates with grain-sizes larger than several microns, often with glassy mesostasis. Heating during atmospheric entry, however, complicates the classification of particles because it results in significant changes in the primary mineralogy, texture and even the compositions of particles. Micrometeorites are, therefore, also divided into several groups depending on the extent of thermal modification during atmospheric entry. The proportion of melted, partially melted and unmelted MMs varies with particle size (Maurette et al. 1991; Taylor et al. 2000). For sizes >100 μm melted MMs make up

70–90% of particles (Maurette et al. 1991; Taylor et al. 2000), for those 50–100 μm in size melted and partially melted MMs make up ~50% of particles (Genge et al. 1997). The most important MM types are described briefly below. Rare groups of particle, such as refractory unmelted MMs will not be described in detail here. A full description of MM types is given in Genge et al. (2008).

3.1 Melted Micrometeorites: Cosmic Spherules

Melted micrometeorites are known as cosmic spherules (CSs) and have experienced large degrees of fusion of primary phases during atmospheric entry and thus behave as low viscosity melts that form molten droplets during atmospheric entry (Fig. 1a–f). The maxima in the extraterrestrial mass flux at ~200 μm (Love and Brownlee 1993) strongly implies that the majority of CSs formed by melting of dust particles rather than as ablation droplets from larger meteoroids.

Cosmic spherules show considerable diversity in textures, compositions and mineralogy and are sub-divided into several chemical and textural groups. The basic chemical sub-types of CSs, which are also reflected in their principle mineralogy, are the iron-rich spherules (I-type), a glass with magnetite (G-type) group (Blanchard et al. 1980) and silicate-type (S-type) CSs. I-type and G-type spherules comprise only a few percent of MMs and consist principally of the iron oxides, magnetite and wüstite.

The silicate S-type make up 97% cosmic spherules (Taylor et al. 2000). Most have broadly chondritic compositions (Brownlee et al. 1997), notable exceptions are the CAT spherules that have Mg/Si ratios >1.7 and are highly enriched in Ca, Al and Ti (Taylor et al. 2000). S-type spherules can be sub-divided into several sub-classes depending on their quench textures, which are thought to reflect their peak atmospheric temperatures (Taylor and Brownlee 1991). These are: (1) CAT spherules that have high Mg/Si ratios, Ca, Al and Ti abundances. These particles are thought to have been partially evaporated during entry heating. (2) Glass spherules (Fig. 1a) which consist entirely of glass, and are thought to have formed at the high peak temperatures. Glass spherules sometimes contain large vesicles. (3) Cryptocrystalline (CC) spherules (Fig. 1b), which contain sub-micron crystallites and can have significant sub-micron magnetite. Their textures are often dominated by elongate olivine dendrite crystals that radiate from the surface of the spherule. (4) Barred olivine (BO) spherules (Fig. 1c), which are dominated by parallel growth olivine, which occurs as parallel bars, within a glassy mesostasis that often contains magnetite. Some BO spherules exhibit FeNi metal beads that have sometimes oxidised to form iron-oxide located at one end of the particle. Barred olivine spherules are thought to form at lower peak temperatures than CC spherules (Taylor et al. 2000). (5) Porphyritic olivine (PO) spherules (Fig. 1e, f), which are dominated by olivine microphenocrysts with equant, euhedral or skeletal morphologies within a glassy mesostasis, usually with accessory magnetite and/or chromite. Relict unmelted olivine (and less frequently pyroxene) are common in PO spherules. PO spherules experienced the lowest peak temperatures of any cosmic spherules, many are highly vesicular and are likely to be gradational to partially melted MMs. Some PO spherules also contain areas dominated by Fe–Ni-metal and/or Ni-bearing sulphides (Fig. 1e, f). These are thought to form as immiscible metallic liquids during heating and are often found at the margins of spherules suggesting they were in the processes of separating during cooling (Genge and Grady 1998).

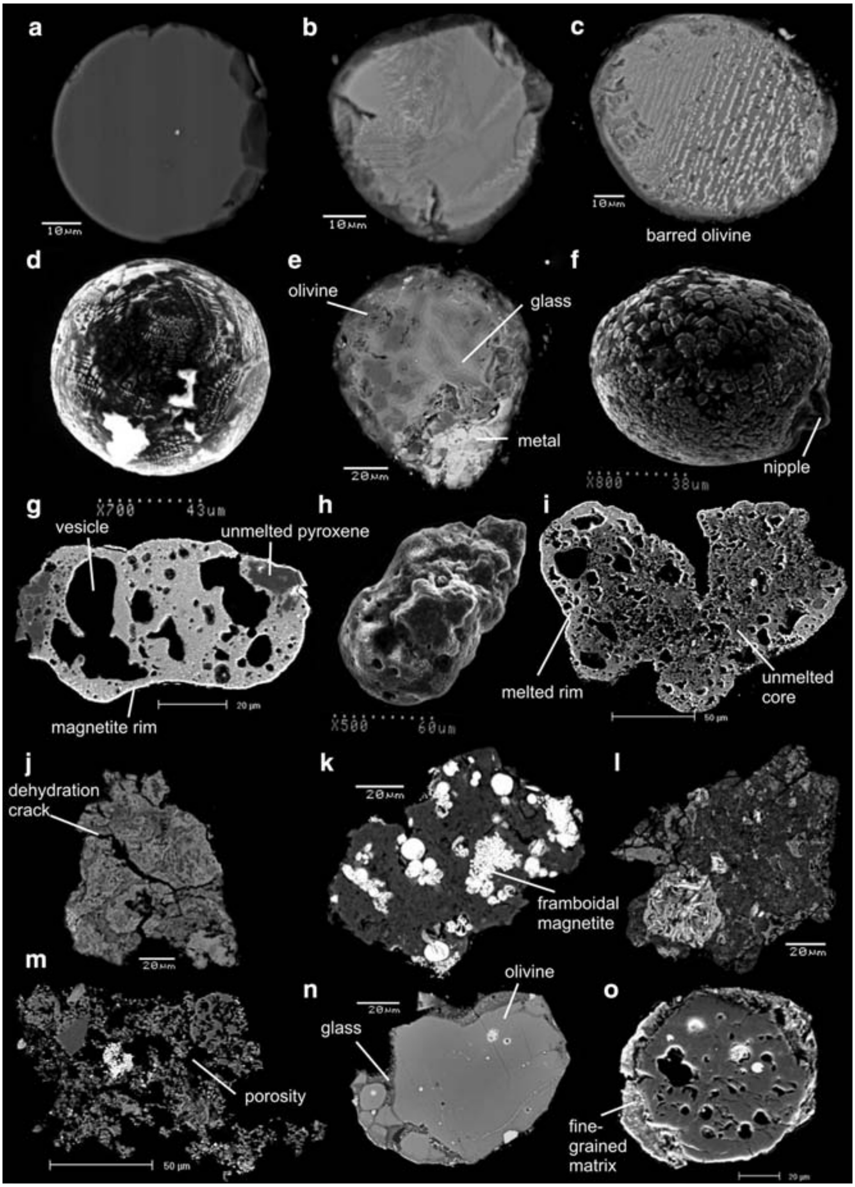

Fig. 1 Scanning electron microscope images of micrometeorites. The backscattered electron images (BEIs) are of polished particles and show interior textures. Contrast in these images relates to atomic mass with bright objects usually dominated by Fe. Particles d, f and h are secondary electron images of the external surfaces of particles. The MM types are (a) glassy cosmic spherule (CS), (b) cryptocrystalline CS, (c) barred olivine CS, (d–f) porphyritic olivine CS, where spherule e contains a metal droplet, and spherule f has a metal separation nipple, (g–i) scoriaceous MMs, where g has relict unmelted crystals, h shows bursting of vesicles on the exterior surface, and i has a large unmelted core, (j) altered fine-grained MM (FgMM) containing dehydration cracks, (k) C1 FgMM, (l) C2 FgMM, (m) C3 FgMM, (n) coarse-grained MM, and (o) composite MM with both coarse-grained and fine-grained portions

3.2 Partially Melted MMs: Scoriaceous Fine-grained MMs

Scoriaceous micrometeorites (ScMMs) are irregular, but smooth, highly vesicular particles (Fig. 1g–i) that have external rims of magnetite. Scoriaceous micrometeorites are dominated by a small olivine crystals, usually with crystal sizes <1 μm, within an interstitial silicate glass phase indicating significant melting, however, ScMMs commonly contain areas of relict fine-grained matrix similar to that of many unmelted MMs (Fig. 1i). Many ScMMs are, therefore, partially melted, consisting of an igneous rim surrounding an unmelted core. These are, therefore, a gradational group to unmelted particles.

The most common relict grains in ScMMs are Mg-rich pyroxene and Mg-rich olivine (Fig. 1g). Vesicle abundances in ScMMs are frequently high and sometimes exceed 50% by volume. Occasionally ScMMs contain Fe–Ni metal/oxides or Ni-bearing sulphides and like those of CSs these may have formed as immiscible metallic/sulphide liquids or by incomplete melting.

3.3 Unmelted MMs

Three varieties of unmelted MMs are identified: (1) fine-grained MMs (FgMMs), (2) coarse-grained MMs (cgMMs) and (3) refractory MMs. Fine-grained MMs are those dominated by a fine-grained porous groundmass of micron-sized mineral grains and are similar to the fine-grained matrices of chondritic meteorites (Fig. 1j–m). Like these materials they have broadly solar compositions (Rietmeijer 2000), mostly in the range of CI, CM and CR chondrite matrices, for most major and minor elements (Genge et al. 1997; Kurat et al. 1994).

The pre-atmospheric mineralogy of fine-grained matrix is thought to have been dominated by phyllosilicates, however, these are rarely preserved. Most FgMMs are dominated by amorphous silicate grains, or sub-micron olivine and pyroxene within glass, both thought to have formed by thermal decomposition of phyllosilicate during entry heating. Dehydration of phyllosilicates is associated with a decrease in volume. Dehydration cracks are thus common in FgMMs. Some heated particles also have melted rims that resemble the matrices of ScMMs (Fig. 1j).

Where phyllosilicates are preserved transmission electron microscope (TEM) and X-ray diffraction studies show they are dominated by smectite (Genge et al. 2001; Gounelle et al. 2002; Nakamura et al. 2001; Noguchi and Nakamura 2000; Noguchi et al. 2002) although serpentine has also been identified (Genge et al. 2001). Despite the thermal modification of particles many, nevertheless, retain their primary textures.

Three broad sub-groups of fine-grained MM are identified: (1) C1 fgMMs that are dominated by compact, chemically homogeneous phyllosilicate-dominated matrix (Fig. 1k) The particles lack isolated olivine and pyroxene, and contain framboidal magnetite clusters. Texturally they resemble the CI chondrites. (2) C2 fgMMs that are dominated by compact, chemically heteorogeneous phyllosilicate-dominated matrix (Fig. 1l). These particles contain isolated olivine and pyroxene grains <10 μm in size and include the mineral tochilinite. Texturally these particles resemble CM2 chondrites. (3) C3 fgMMs, which are porous, chemical heterogeneous particles dominated by micron-sized olivine and pyroxene (Fig. 1m). These particles contain larger (<10 μm) isolated olivine and pyroxene grains and have no direct meteorite analogs. Primary differences from chondrites, for example, in the high pyroxene to olivine ratios of MMs and the exact mineralogy of matrix are also evident (Maurette et al. 1991).

Unmelted coarse-grained MMs (CgMMs) usually have igneous textures and are dominated by olivine, pyroxene crystals within glassy mesostasis (Fig. 1n). They often contain either metal and sulphide, or iron oxides. The textures of CgMMs fall largely into four sub-groups: (1) porphyritic particles, dominated by crystals within a glassy mesostasis, (2) granular particles, dominated by olivine and pyroxene with little glass, (3) radiating pyroxene particles, dominated by elongate dendritic crystals of pyroxene that radiate across the particle, and (4) barred olivine particles, containing bar-like crystals of olivine within pyroxene or glass. All these textural groups are similar to those of chondrules, mm-sized igneous objects within the chondritic meteorites. The minor element compositions of olivine and pyroxene within these particles are likewise consistent with those of chondrules from carbonaceous and ordinary chondrites (Genge et al. 2005).

Refractory MMs are rare particles containing Ca–Al–Ti rich minerals, such as hibonite, perovskite, melilite and spinel, which are associated with CAIs from chondritic meteorites. The majority of these particles contain isolated grains of refractory minerals within a FgMM, however, particles dominated by refractory minerals have been observed.

Composite unmelted MMs have also been observed that contain portions characteristic of both CgMMs and FgMMs (Genge 2006). Such particles usually consist of a coarse-grained, igneous-textured object dominated by anhydrous silicates and glassy mesostasis, surrounded by a partial rim of fine-grained matrix (Fig. 1o). They indicate that CgMMs and FgMMs can be derived from the same parent bodies and that CgMMs are present as small objects similar to chondrules.

4 Implications for Meteors

4.1 Survival of Micrometeoroids

Ceplecha et al. (1998) suggest that typical meteors are associated with micrometeoroids 0.05 mm–20 cm and at least a proportion of micrometeorites, therefore, may be the surviving remnants of meteors. Meteoroid velocity is also, however, a crucial parameter since observation of meteoric phenomena requires evaporation of the meteoroid by heating by incident air molecules to form a plasma within the meteor trail. High velocity meteoroids which experience significant evaporation are more likely to be observable but are less likely to be preserved as micrometeorites. Ionisation of gas species is particularly important since the light produced by optical meteors largely originates from the de-excitation of metals by radiation and observation by radar depends on the density of free electrons in the meteor trail. Ionisation temperatures are >3,000 K (e.g. Ceplecha et al. 1998), however, evaporation rates of silicate liquids become extremely high at temperatures >2,200 K with the result that the surface temperatures of 100 μm droplets are unlikely to exceed this limit (Schaefer and Fegley 2004). Observations of meteors produced by meteoroids of this size, therefore, suggest that gas temperature and meteoroid surface temperature are not the same, presumably due to excitation of gas species by direct collections with incident air molecules. Micrometeoroids which lose sufficient mass through evaporation potentially could be observed as meteors.

Entry heating models indicate that CSs, in particular large mm-sized spherules, can lose 90% of their mass through evaporation during atmospheric entry (Love and Brownlee 1991) and potentially represent the surviving meteoroids of meteors. The compositions of most CSs, however, are solar (e.g. Genge et al. 1997) and do not support changes due to differential ablation that would be expected during significant evaporative mass loss. Only

CAT spherules, which are enriched in refractory elements such as Al and Ca, are consistent with such extreme evaporative fractionation (Taylor et al. 2000).

Micrometeorites are most likely to survive atmospheric entry unmelted at low entry velocities (Love and Brownlee 1991) implying these are derived from low geocentric velocity sporadic sources. The mineralogy, textures and compositions of unmelted MMs support this inference since they are similar to chondritic meteorites and thus imply an asteroidal source (e.g. Genge et al. 1997, 2008). The occurrence of abundant phyllosilicates in MMs in particular differs from prevailing models of cometary nuclei, and the results from comet Wild-2 particles (Brownlee et al. 2006). The presence of phyllosilicates in comets, however, remains controversial (Gounelle et al. 2006; Lisse et al. 2006; Rietmeijer 1998). Low geocentric velocity cometary dust particles may, nevertheless, exist particularly amongst highly porous FgMMs.

Anhydrous IDPs, which are aggregates of sub-micron silicate grains contained within carbonaceous material, have been considered to represent cometary materials, a view that is broadly consistent with the early results of the Stardust Mission (Brownlee et al. 2006). Refractory Ca–Ti-rich particles and silicate igneous objects, reminiscent of microchondrules, however, have been discovered amongst Stardust samples (Brownlee et al. 2006) implying that comet Wild-2 shares some mineralogical and textural features with MMs and chondritic meteorites.

Micrometeorites are, therefore, directly analogous to the meteoroids of sporadic meteoroids derived from asteroidal sources. They may also provide constraints on the nature of cometary meteoroids that produce meteor showers, given the uncertainty in the nature of these materials. A proportion of CSs may also be derived directly from cometary sources since entry heating models suggest these can survive atmospheric entry at high velocities of >30 km s^{-1} (Love and Brownlee 1991). It is, however, unlikely that meteoroids from meteor showers are common amongst MMs due to their high entry velocities.

4.2 Entry Heating Phenomena of Meteoroids

Although unmelted MMs are samples of relatively low geocentric velocity dust particles the mineralogical and physical changes they experience during atmospheric entry heating have applications to meteor phenomena in general, including those from high entry velocity streams, since the meteoroids of all meteors experience a degree of pre-heating during non-luminous flight that can modify their physical and chemical properties. Such changes allow definite predictions to be made that potentially can relate the material properties of micrometeoroids to their deceleration and evaporation rates.

The onset of melting is likely to have a significant effect on the atmospheric entry heating of micrometeoroids. Partially melted MMs indicate that phyllosilicate-bearing particles experience surface melting in which high temperature gradients (>600°C) are supported by endothermic dehydration reactions (Genge 2006). Continued heating of such micrometeroids leads to progressive fusion of the solid core of the particle. Due to the latent heat of fusion and the high thermal conductivity of silicate melts the surface melt layer will remain at the melting temperature of the fine-grained matrix ($\sim$1,350°C) until the solid core has been consumed. The surface temperature of micrometeoroids, and thus their evaporation rates, will, therefore, remain constant over a portion of the entry heating. Isothermal surface temperatures apply only to particles containing volatile-bearing phases such as phyllosilicate.

Melting of micrometeoroids during entry heating also results in changes in the density and volume of particles that influences their deceleration. These changes depend on the material properties of the micrometeoroid. Compact particles, such as cgMMs, experience a decrease in density during melting from that of the crystalline solid aggregate (>3.0 g cm^{-3}) to a partially melted material as glass begins to melt. On fusion their densities will decrease smoothly with temperature as they partially melt towards that of a ferromagnesian melt of approximately 2.7 g cm^{-3}.

The change in density of FgMMs on melting is likely to depend on the abundance of vesicles formed by the exsolution of gases from volatile components. Unmelted compact FgMMs have densities similar to CI chondrites of $\sim$2.1 g cm^{-3} (Britt and Consolmagno 2003), however, high porous particles may have densities as low as 1.0 g cm^{-3}. The abundance of vesicles in ScMMs often approaches 50% by volume, suggesting the density of the molten particle will evolve towards 1.3 g cm^{-3}. The significant decrease in the density of compact phyllosilicate-bearing particles is associated with an increase in the volume of the particle and thus will produce a pronounced increase in the deceleration of the micrometeoroid. With increasing temperature the decrease in melt viscosity will allow escape of vesicles from the molten micrometeoroid, as indicated by the decrease in vesicle abundances from ScMMs to CSs. Particle density will, therefore, increase with heating towards that of the melt. The presence of unmelted olivine and pyroxene will, however, result in slightly higher densities.

Within cometary micrometeoroids, vesicularity is also likely to play a significant role. If these objects are similar to anhydrous IDPs, they may have densities as low as 0.6 g cm^{-3} (Flynn and Sutton 1991). The density change on melting is likely to be sensitive to the degassing prior to fusion. If the particle does not significantly degas it is likely to become a highly vesicular foam on melting (e.g. Rietmeijer 1996) and thus retain its low density. If it does degas prior to melting there will be a significant increase in density and decrease in volume.

Molecular gas species generated during degassing of micrometeoroids will vary with particle type. Phyllosilicates will release water vapour during dehydration, carbonaceous materials will generate CO_2 as a result of pyrolysis, and sulphides are likely to generate both SO_2 and H_2S on decomposition. Highly volatile components are likely to be released during pre-heating of meteors, however, the presence of vesicles within cosmic spherules suggests that some may be retained into luminous flight. Emission from molecular gas species has yet to be detected in meteors.

4.3 Fragmentation of Micrometeoroids

Meteor fragmentation events are a function of the mechanical properties of micrometeoroids. The nature of MMs allows fragmentation events to be interpreted in terms of the material properties of micrometeoroids. The break-up of solid meteoroids is likely to occur during the pre-heating of meteors prior to luminous flight and result in a burst of closely related meteors.

Fragmentation of phyllosilicate-bearing particles is likely to occur during dehydration of the fine-grained matrix due to the formation of dehydration cracks. These represent planes of mechanical weakness and are likely to dictate the size of secondary particles during fragmentation events. Examination of MMs suggests that fragmentation due to dehydration cracks will lead to 2–5 fragments with diameters $\sim$0.25–0.5 times that of the original particle, and a second population of particles with diameters <0.1× that of the original particle.

Cometary, IDP-like micrometeoroids, are also likely to experience decomposition of their volatile carbonaceous components prior to melting which may likewise lead to fragmentation. Mechanical disaggregation of the carbonaceous "glue" of such particles is likely to result in liberation of the sub-micron sized silicate grains contained within the meteoroid. Sudden fragmentation to sub-micron-grains is, therefore, likely to be a feature of IDP-like micrometeoroids, although similar fragmentation may also occur for the most porous and fragile FgMM-like particles, albeit to micron-sized mineral grains.

Compact igneous particles, similar to chondritic cgMMs, that may largely represent pieces of chondrule, are mechanically strong objects and unlikely to fragment during deceleration. Composite particles, that include both fine-grained portions and coarse-grained portions, however, may break-up into a single large fragment and a range of micron-sized grains.

Fragmentation of molten micrometeoroids is problematic since continuous ablation due to the removal of surface melt is only expected for larger meteoroids in the slip-flow regime. Most micrometeroids <400 μm have a size much less than the mean-free path of atmospheric species and thus decelerate in the free molecular flow regime in which there is no shear component over the surface of the particle. The development of instabilities in droplet shapes has been suggested as a potential mechanism for the fragmentation of molten particles, however, for small droplets surface tension is likely to strongly resist the development of instabilities (Bronshten 1983). The regular shapes of CSs suggest that such instabilities are rare.

The presence of metal and iron-sulphide droplets within some CSs provides one mechanism by which fragmentation of molten particles may occur. Metal and iron sulphide are generated either by non-equilibrium melting of large pre-existing mineral grains or through redox reactions during melting. Metal generation through redox reactions should be relatively common within carbon-rich micrometeoroids, similar to fgMMs and IDPs, since on melting carbon reacts with oxygen within the melt to form CO_2 leading to reduction of Fe^{2+} in the melt to metallic Fe^0 (Genge and Grady 1998). Amongst MMs there is evidence from the compositions of spherules that metal separation during to deceleration is common.

Once generated the higher density of the metallic liquid than the silicate melt leads to migration of the metallic liquid to the leading surface of the meteoroid, to form a surface protrusion, which in many cases will then separate entirely. Only metal droplets that failed to separate are preserved amongst MMs. Metal separation will result in fragmentation into two droplets, a high density (~ 8 g cm^{-3}), small droplet, and a lower density, larger silicate droplet. Due to the differences in size and density the metal droplet will experience less deceleration after separation and thus will rapidly move ahead of the silicate sphere. The exact relative acceleration will depend on the sulphide to metal content of the droplet, and the degree of oxidation of the metal, since these will influence the density of the iron-rich liquid. The occurrence of metal separation events, which can be identified by the relative deceleration of the produced meteoroids, implies the precursor meteoroid either contained metal grains, or was carbon-rich, prior to melting. Meteors with iron dominated spectra (Type Z meteors; e.g. Ceplecha et al. 1998), may, therefore, represent separated metal droplets rather than primary compositional variations in the precursor meteoroids.

5 Conclusions

The nature of unmelted MMs suggest that the majority of these particles represent asteroidal materials and thus probably correspond to low geocentric velocity sporadic meteors rather than meteor streams. The nature of melted MMs, nevertheless, has implications for the atmospheric entry behaviour of meteors in general. Specifically: (1) melted rims on phyllosilicate-bearing MMs indicates these particles have thermal gradients and isothermal surface temperatures, (2) highly vesicular partially melted particles indicate large changes in meteoroid volume and density on melting, (3) dehydration cracks in phyllosilicate-bearing MMs provide a mechanism for fragmentation that is distinct from anhydrous IDP-like particles, and (4) metal separation from CSs provides a mechanism for fragmentation of molten micrometeoroids.

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